

Modeling of Lunar Dust Contamination Due to Plume Impingement

Michael Woronowicz, SGT Inc.

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Introduction (1 of 3)

- Apollo 16 Lunar Module landing sequence



- “I think dust is probably one of our greatest inhibitors to a nominal operation on the Moon. I think we can overcome physiological or physical or mechanical problems except dust.”
 - *Gene Cernan, Apollo 17 Technical Debrief*

Introduction (2 of 3)

- During the Apollo missions it became apparent that lunar dust was a significant hazard. Problems included
 - Surface obscuration during landing sequence
 - Abrasion damage to gauge faces and helmet visors
 - Mechanism clogging
 - Development of space suit pressurization leaks
 - Loss of radiator heat rejection capabilities to the point where vulnerable equipment exceeded maximum survival temperature ratings
 - Temporary vision and respiratory problems within the Apollo Lunar Module (LM)

Introduction (3 of 3)

- NASA Constellation Program features many system-level components
 - including the Altair Lunar Lander
- Altair to endure longer periods at lunar surface conditions
 - Apollo LM, about three days
 - Altair, over seven months
- Program managers interested in plume-generated dust transport onto thermal control surface radiators of the first Altair created by its own landing operations

Problem Description

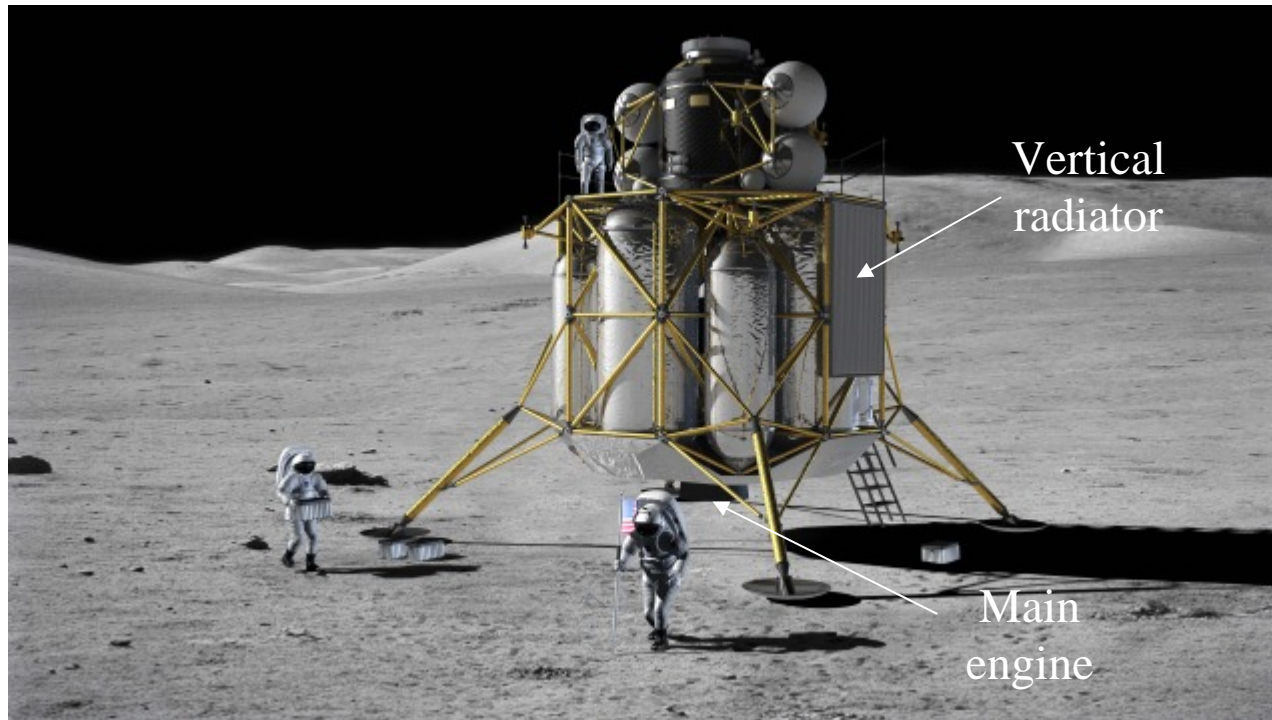
- Analyze dust contamination environment generated during first Lunar Lander landing
 - Self-contamination of critical thermal control radiators
 - Non-LOS
- Virtually no lunar atmosphere
 - No atmospheric mixing of gases
- Concern that electrostatically-charged particles, freed from lunar regolith by lander engine operations, may find their way to critical lander surfaces

Approach

- Model main engine plume
- Calculate surface stresses on lunar regolith
- Calculate regolith removal rate
 - Fluid acceleration against particle inertia, short-range forces
- Determine electrostatic work necessary to overcome kinetic energy of mobile dust particles
- Current modeling efforts still underway

Altair Lunar Lander

- Much larger than Apollo Lunar Lander
 - 46,000 kg vs. 16,400 kg
- Meant to remain on lunar surface for weeks
 - Period depends on type of mission (sortie vs. outpost support modes)



Pratt & Whitney RL-10 Engine Description

- Created RL-10 model
 - Hard to pin down unspecified Altair parameters
 - Range of O/F ratios
 - Various I_{sp} 's, nozzle geometries
 - Versatile engine, designed in 1957, has used vast array of fuels under test conditions, throttled down to 1% full thrust in testing
 - Used RL-10A-4 info
 - $I_{sp} = 449$ s, O/F = 5.5, $p_0 = 39$ bar, $\dot{m} = 21$ kg/s, $A_e/A^* = 84$
 - Nozzle exit properties (simplistic)
 - $22 \text{ H}_2\text{O} + 10 \text{ H}_2$
 - $V_e = 4.3$ km/s, $T_0 = 2600$ K, $T_e = 550$ K, $M_e = 6.37$
 - Decided flat exit profile adequate for current application
 - Neglect boundary-layer development and its high-angle influence
 - Altair geometry inhibits backflow development

Descent Engine Comparisons

- Altair RL-10 vs. Apollo LM Descent Stage (DS)
 - Fuel
 - LOX/LH₂ vs. N₂O₄/Aerozine-50
 - Thrust
 - 99.1 kN vs. 44.0 kN
 - Specific Impulse I_{sp}
 - 449 s vs. 311 s
 - Exit velocity
 - 4.3 km/s vs. 3.1 km/s
- Altair DS engine parameters much more energetic than Apollo
 - Apollo-related models may not be suitable for Altair investigations

Observations

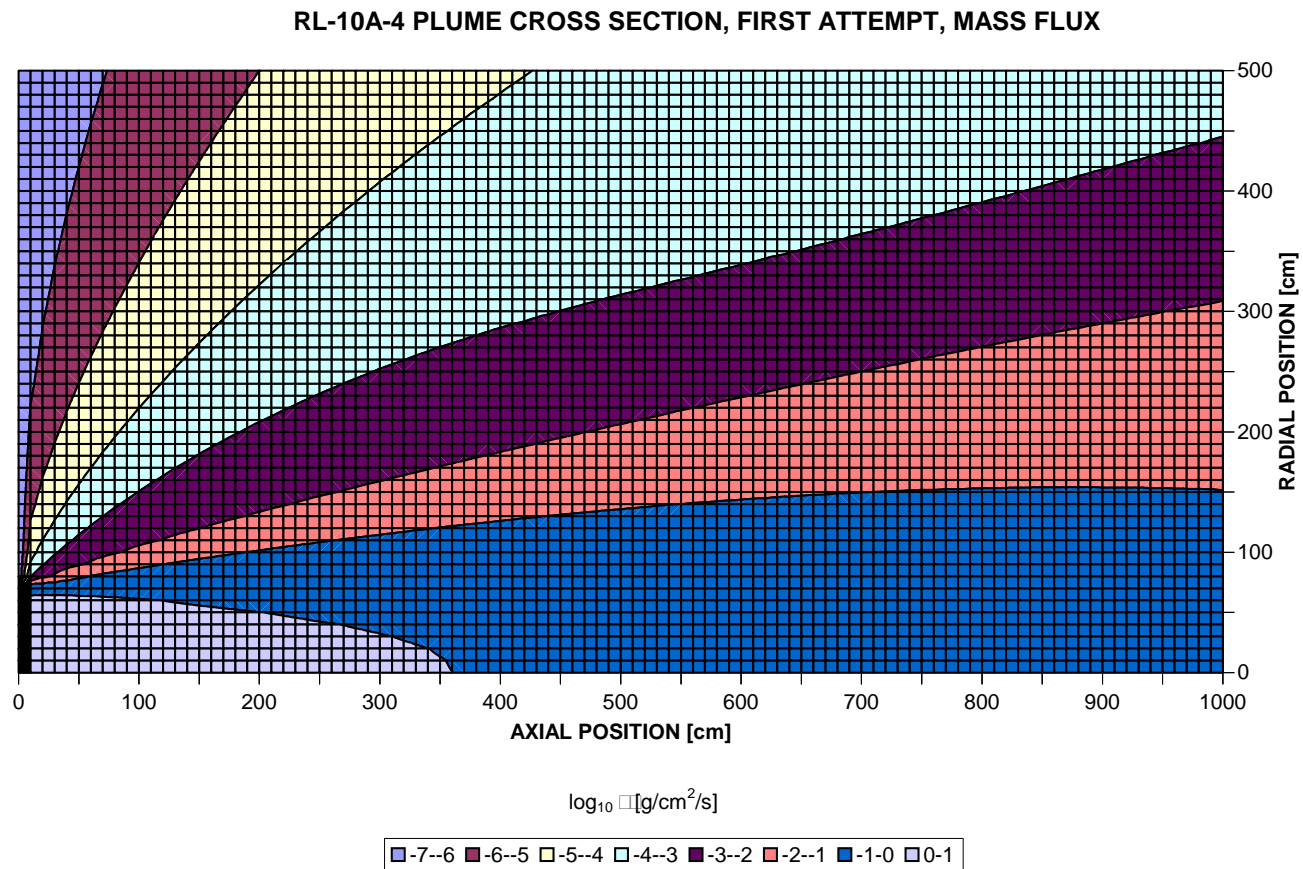
- Period of highest plume impingement not same as period of worst dust attraction
- Particle drag will overwhelm charge effects
 - Neglect dust attraction during firing periods
 - Drag force and attraction both fall with square of distance
- Attraction occurs during, after engine shutdown
 - Only for disturbed, charged dust within Debye radius from Lander
 - Intersection with lunar surface produces disk of influence
 - Varies with particle size, relative potential

Plume Model Formulation

- Initial modeling uses FM plume formulation
 - Can use rapidly to approximate incident fluxes (impingement stresses)
 - Try correcting for Knudsen layer using bridging technique
 - DLR
 - Potter
 - Reynolds analogy for high density shear (Legge)
- Can substitute results from different approaches
 - DSMC simulations
 - CFD computations

FM Model—Free Expansion

- Logarithmic mass flux contour map

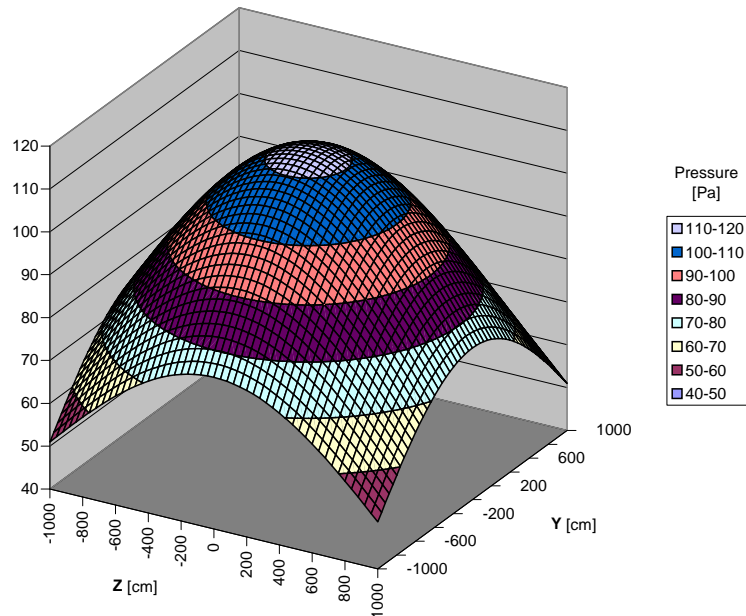


- Mass flow rate verified from mass flux map

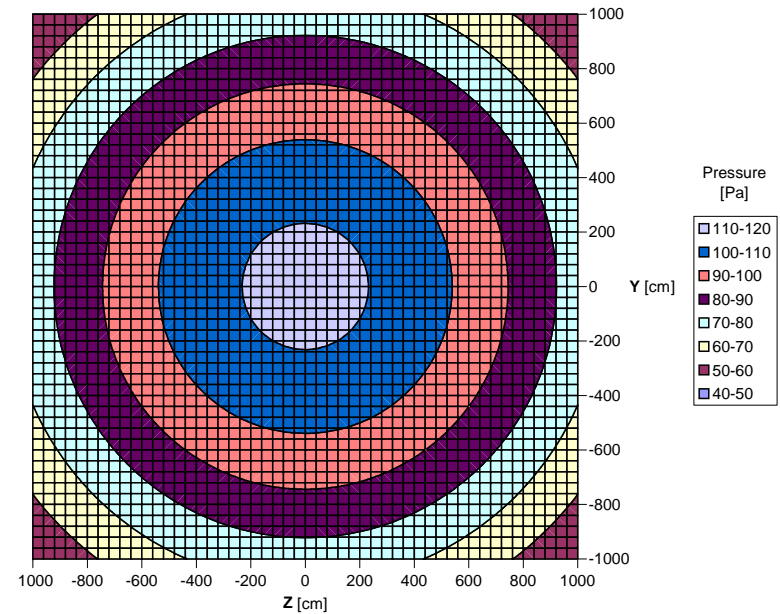
FM Model—Surface Impingement

- Pressure contours (incident + reflected, $T_{\text{surf}} = 300 \text{ K}$)

RL-10A-4 LUNAR SURFACE IMPINGEMENT
SURFACE PRESSURE FROM 100 m ALTITUDE

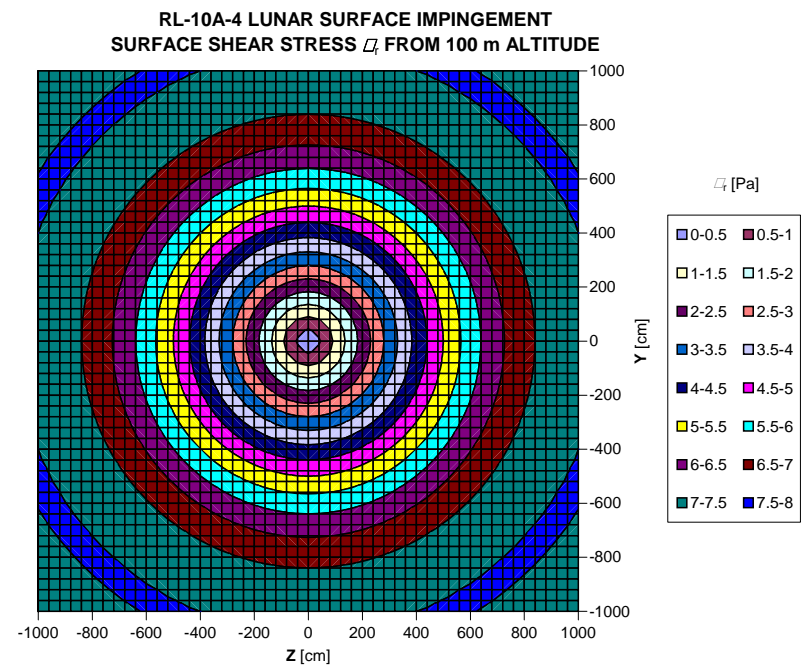
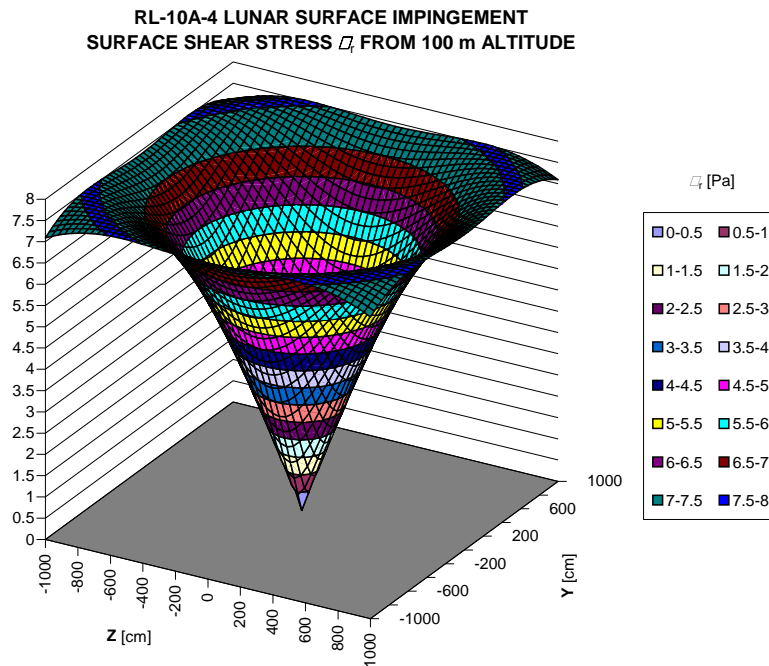


RL-10A-4 LUNAR SURFACE IMPINGEMENT
SURFACE PRESSURE FROM 100 m ALTITUDE



FM Model—Surface Impingement (cont.)

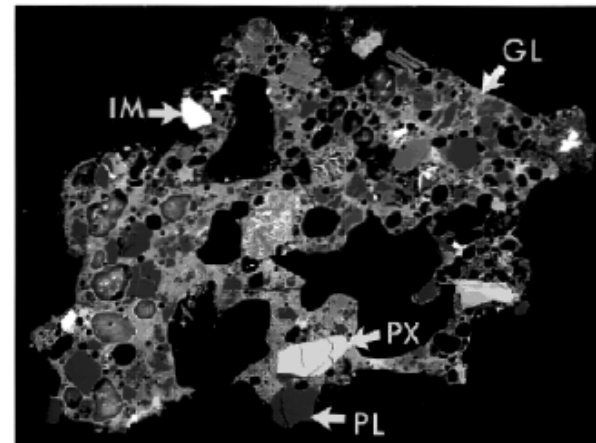
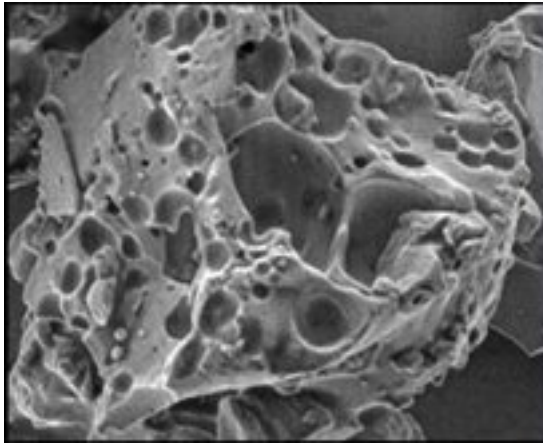
- Radial shear stress contours
 - Max of 7.5 Pa @ $r = 11.3$ m



Plume Model Procedure

- Create time-varying gas properties across starting surface
- Inputs at each timestep affects solution domain over long subsequent period
 - May identify arbitrary response periods to individual input timestep conditions beyond which influences decay to negligible values
 - Build up overall FM solution from summation of transient responses to inputs at each single timestep
- Look for opportunities to revise with solutions using higher-fidelity techniques
 - DSMC, CFD, hybrids

Lunar Dust Attributes



(Frame width ≈ 0.66 microns)

Lunar Dust Attributes

- Typical sample described as a basaltic ash
- Density $\approx 2.9 \text{ g/cm}^3$
- Avg. grain radius ≈ 70 microns
 - Size distribution ranges from sub-micron to hundreds of microns
- Jagged features
 - Oxidation removes roughness for terrestrial dust
 - Exposure to high-energy solar wind
- Low electrical conductivity
- Surface adhesion facilitated by
 - Burr-like geometry
 - Electrostatic effects

Dust Production Mechanism

- “Viscous erosion” model developed for Apollo program
 - Issue concerned obscuration of landing site, not charged particle attraction
- Particle expected to remain at rest until local plume shear stress overcomes static friction, cohesive stress, component of gravity
 - Does this process produce triboelectric charging?
- Plume shear stress in excess of the critical value converted into accelerating particles to their final velocities
- Some subsequent testing found model erosion rates match to within an order of magnitude
 - Verification of particle velocities not mentioned

Observations

- Viscous erosion model
 - assumes instantaneous acceleration to final velocity
 - Neglects persistent influence of plume environment
 - Model assumes dust trajectories determined by surface ejection angle
 - Recent photogrammetric analyses indicate actual trajectories lie 1-3° off horizontal
 - Effects on dust velocity
- Current studies identify at least three other mechanisms
 - “Bearing Capacity Failure”
 - “Diffused Gas Eruption”
 - “Diffusion-Driven Shearing”
- Erosion model modifications currently under development

Electrostatic Attraction to Altair

- Compute Debye radius
 - Representative distance over which significant charge separation can occur and still exert influence
 - Outside this distance, charges are considered screened
- Time lag determines whether generated particles remain within influence disk (intersection of Debye sphere and lunar surface) at instant engine firing ceases
 - Sorta like “musical chairs” once music stops
- Electrostatic attraction model
 - Electrostatic work performed to overcome K.E. for Altair surface attraction
 - Translate these effects to a incident dust mass flux

Final Results--Dust Mass Flux

- Dust return flux will be particle size dependent
 - Must use binning to create return fractions
 - Summation provides estimate for Percent Area Coverage (PAC)
 - Assume no overlap of particles (simple, conservative for high PAC's)
- Relate PAC to radiator degradation
 - Changes in absorptivity, emissivity
- Others could use mass flux to determine effects on mechanisms, visors, etc.

Concluding Remarks

- Relatively unique investigation requires at least three models
 - Transient plume impingement problem
 - Dust generation rates
 - Non-line-of-sight electrostatic attraction
- Must remain responsive to possibility of incorporating
 - high-fidelity RL-10 lunar plume impingement computational results
 - updates to dust generation models from current studies
 - Including newly-defined generation mechanisms
 - Estimates of charging of lunar surface, Altair due to various mechanisms